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Title: Multipurpose Acoustic Sensor for Downhole Fluid Monitoring

Author(s): Pantea, Cristian

Intended for: Report

2012 Geothermal Technologies Peer Review
Summary: Acoustic Sensor for Downhole Fluid

1. Multipurpose Acoustic Sensor for Downhole Fluid Monitoring

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- Subcontractors and Participating Organizations: N/A

2. Project Objectives and Purpose

- Develop a multipurpose acoustic ***sensor*** for downhole fluid monitoring in Enhanced Geothermal Systems (EGS) reservoirs over typical ranges of pressures and temperatures and demonstrate its capabilities and performance for different EGS systems.
- Determine in real-time and in a single sensor package several parameters: temperature, pressure, fluid flow and fluid properties.
- Needed in nearly every phase of an EGS project, including Testing of Injection and Production Wells, Reservoir Validation, Inter-well Connectivity, Reservoir Scale Up and Reservoir Sustainability.
- Current sensors are limited to operating at lower temperatures, but the need is for logging at high temperatures. The present project deals with the development of a novel acoustic-based sensor that can work at temperatures up to 374°C, in inhospitable environments.

3. Technical Barriers and Targets

- This project addresses directly the Site/Well Characterization Barrier D: Characterization – Subsurface environments in EGS regimes are inhospitable to existing downhole, in-situ characterization methods.
- Demonstrate sensor capabilities that can be employed at a depth of 220 bar and operation temperatures of 374°C.
- Technical targets
  Task 2: Theoretical Modeling and Algorithm Development (Jan 2010-Sep 2012)
  Task 3: Sensor geometry (Jul 2010 – Sep2012)
  Task 4: Flow measurement and fluid composition (Apr 2011 – Sep 2012)
  Task 5: Temperature and pressure calibration (Jul 2011 – Sep 2012)

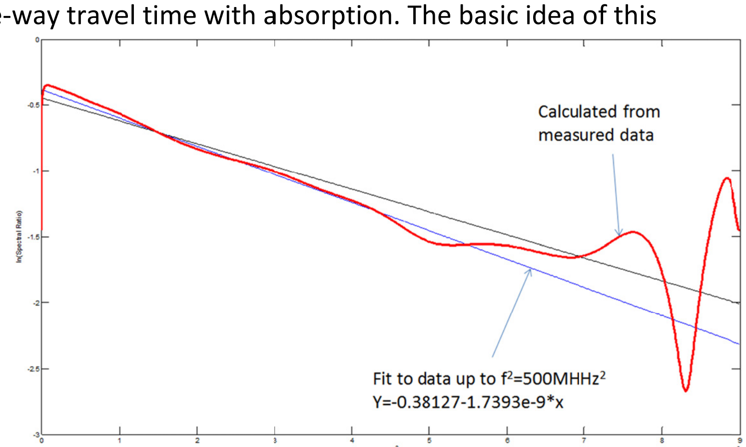
4. Technical Approach

- This project proposes a novel sensor design that is based on acoustics and can determine in real-time and in a single sensor package several parameters: temperature, pressure, fluid flow and fluid properties. A versatile sensor such as this also has similar applications in several industries including the oil and gas industry, chemical industry, pharmaceutical industry and there are excellent opportunities to partner with such industries as the project progresses.

- The underlying physical basis of the sensing technique proposed here is Swept Frequency Acoustic Interferometry (SFAI) and resonance tracking. We propose to adapt SFAI and combine certain new approaches to extract multiple fluid parameters from a single sensor. The SFAI technique involves the determination of the frequency response of a solid container and the fluid inside it over a wide frequency range. This spectrum consists of a series of regularly spaced resonance peaks that originate from standing waves set up in the fluid-filled sensor cavity.
- The ***sound speed*** is determined from the frequency spacing between any two consecutive resonance peaks while the width of the peaks as a function of frequency is related to the ***sound attenuation*** in the fluid. Additionally, a more complex data analysis can provide other fluid properties, including fluid composition, viscosity, and density. For every material, there is an interdependent relationship between its fundamental acoustic resonance frequency and temperature, which enables accurate ***temperature*** determination. A cross-correlation analysis of the frequency spectrum on a dual electrode design on the piezoelectric cylinder provides ***fluid flow*** measurement.
- Fluid composition including density and viscosity at various depths in a borehole provides geothermal reservoir properties.
- Borehole temperature at various depths provide diagnostic measurements for geothermal reservoir characterization: determines thermal gradient along the borehole, provides location of borehole fracture intersections, allows estimation of thermal drawdown, and recovery rates of the circulating systems. The temperature provides diagnostic data during drilling, cementing, pressurization, and hydraulic-fracturing operations.
- Borehole pressure at various depths determines pressure gradient along the borehole, provides location of borehole fracture intersections, can provide information related to recovery rates of the circulating systems.
- Fluid flow determination provides fluid-flow patterns in a borehole. A typical borehole has fractures in several zones. The fluid flow can help characterize the man-made reservoir by: determining the nature and location of the fractures, determining the location and the amount of fluid that leaves and enters the borehole, and determining the relative contribution of each fracture to the total reservoir.

5. Technical Accomplishments

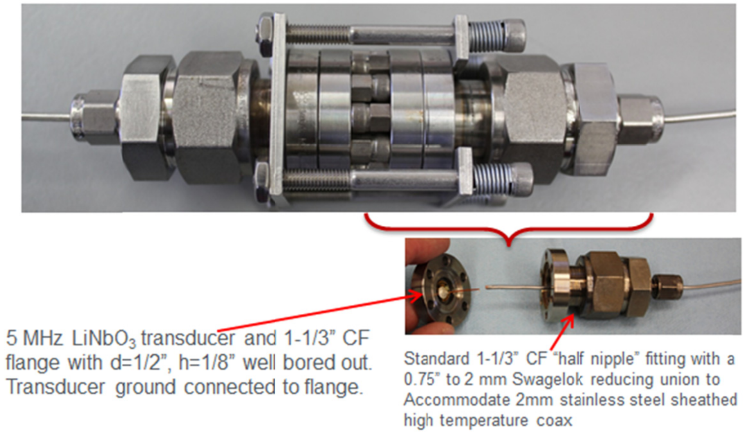
- Task 2: Theoretical Modeling and Algorithm Development
  On schedule, started Jan 2010, initially scheduled for completion: Sep 2012.
  Developed algorithm for sound absorption determination and coded in Matlab, based on dependence of the spectral ratio of the one-way travel time and three-way travel time with absorption. The basic idea of this method consists of: (i) transforming the spectrum to the time domain, (ii) time gating the signal so one has one data set representing a single transit and another representing the triple transit, (iii) converting these data sets back to the frequency domain, (iv) plotting the ratio of the power spectra and (v) fitting the resulting data with a straight line, the slope of which is proportional with sound absorption in the medium of interest:



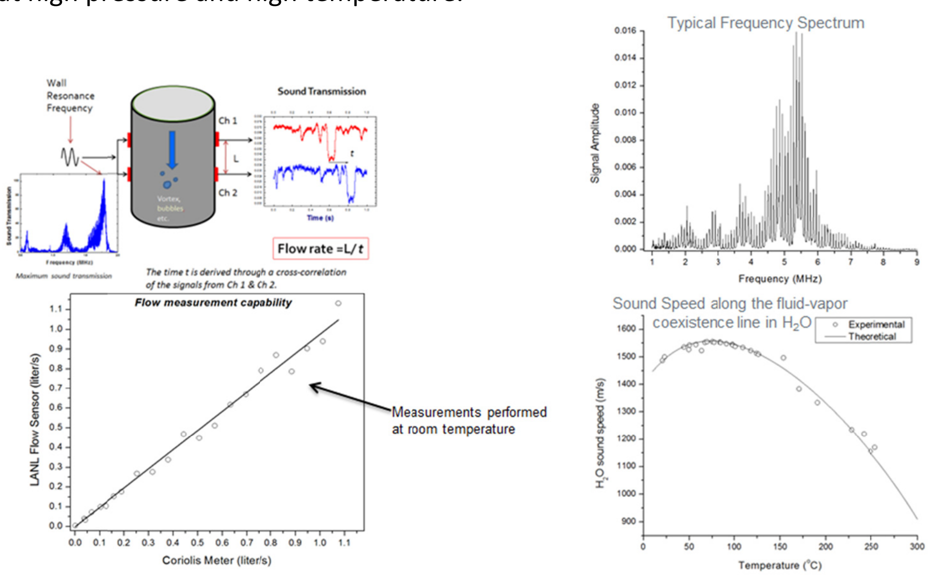
$$\ln\left(\frac{spectrumB}{spectrumA}\right) = -2\alpha L f^2 + \ln(R^2)$$

  The line fit of the spectral ratio is given below, resulting in good agreement with literature data (α/f^2: 0.108 current experiment vs. 0.092 literature, in $m^{-1}MHz^{-2}$).
- Task 3: Sensor Geometry
  On schedule, started Jul 2010. Scheduled for completion: Sep 2012

Experimented with lithium niobate transducers mounted on different sensor geometries. Temperature/pressure range: 270ºC/22 MPa (as of Mar 2012). Progressing according to schedule.

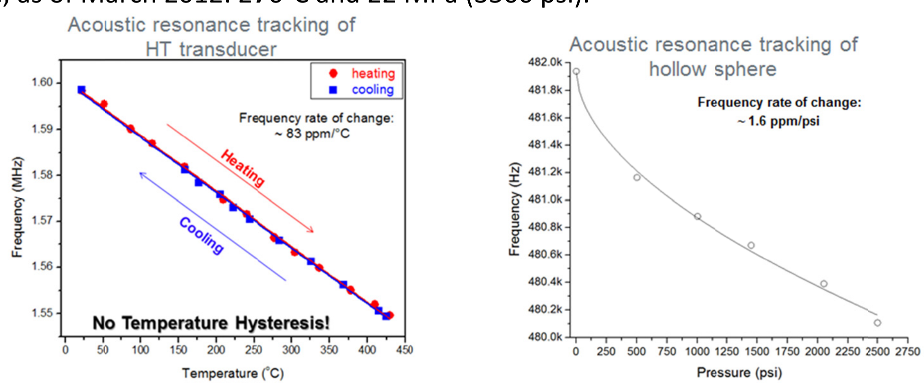


- Task 4: <u>Flow Measurement and Fluid Composition</u>
  On schedule, started 4/2011. Initially scheduled for completion: Sep 2012
  Collected data for water flow in an in-house flow-loop, at room temperature, and various data for fluid composition at high pressure and high temperature.



Current max temperature and pressure, as of March 2012: 270°C and 22 MPa (3500 psi).

- Task 5: <u>Temperature and Pressure Calibration</u>
  Projected start 7/2011, but performed preliminary experiments.
  Scheduled for completion: Sep 2012
  Carried out temperature experiments with $LiNbO_3$ resonators in furnace and pressure experiments with hollow spheres in the pressure chamber. Demonstrated very good sensitivity to temperature and pressure change.
  The sensitivities are given in the figure on the right.



6. Challenges to Date

- Survivability of adhesives in high temperature liquid environment
  - Identified electrically insulating adhesive that withstands harsh test conditions.
  - Have acquired several promising candidates for electrically conductive adhesives.

7. Conclusion and Plans for the future

- The DOE Geothermal Technologies Program recently released two documents related to:

(1) High-priority technology needs into targeted technology focus areas. In the "Well Logging Tools" category, the target temperature for High Temperature Tools for year 2020, is 300°C. Currently we are up to 270°C, and we are confident we can improve on this by Sep 2012.

Well Logging Tools

Advance logging tool technology as applied to geothermal

Technology Advancement	Technology Metrics			
	Metric Unit for Advancement	2011 Status	Target	When
Higher temperature tools	Temperature (°C)	150-200°C	300°C	2020
Slimhole geothermal logging tools	Diameter (in)	150-200°C	≤3"	2016

(2) Technology needs specific to EGS reservoir characterization, creation, and sustainability/operation. In the "High Temperature Logging and Imaging Tools" category, the set target for 2018 is ±10% precision for pressure, temperature and flow. It is to be noted that our lab measurements have already reached the targets set for 2018.

High Temperature Logging & Imaging Tools

Real-time mass "fluxometer" and integrated pressure/flow/temperature tool

Technology Advancement	Technology Metrics			
	Metric Unit for Advancement	2011 Status	Target	When
Mass "fluxometer"	Mass flux accuracy (l/s)	NEW	+/- 0.2 l/s	2015
Integrated Pressure/Flow/ Temp (PFT) Testing Tool	Precision (P, m/s, and T)	+/- 50%	+/-10	2018

- Performed successful sound speed measurements up to 270°C and tested components up to 374°C.
- Modeling and analysis software development progressing according to schedule.
- Performed pressure and temperature determination.
- Flow measurements: experimental determined flows in good agreement with Coriolis meter.
- The work on tasks 4 and 5 started, and the progress is according to the schedule

  Task 4: Flow measurement and fluid composition (Apr 2011 – Sep2012)
  - Milestone: Determine fluid composition and flow for fluids characteristic to EGS (M4).

  Task 5: Temperature and pressure calibration (Jul 2011 – Sep 2012)
  - Milestone: Determine the relationship between pressure, temperature and transducers resonances (M5)

8. Publications and Presentations

- Publications:

B.T. Sturtevant, C. Pantea, D.N. Sinha, *Improved digitized method for pulse-echo measurements and bond corrections*, submitted to J. Acoust. Soc. Am., *in review*

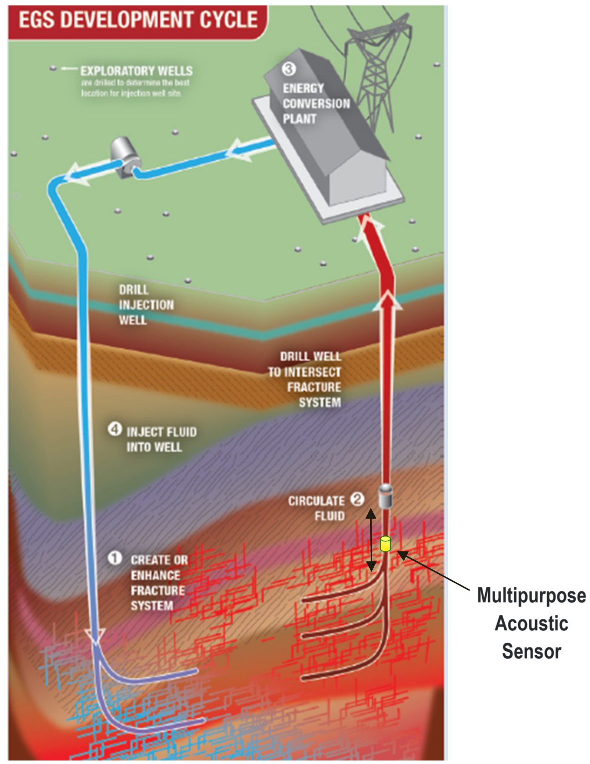
B.T. Sturtevant, C. Pantea, D.N. Sinha, *Novel sensor for fluid properties determination at conditions of high pressure and high temperature*, in preparation.

B.T. Sturtevant, C. Pantea, D.N. Sinha, *Determination of sound speed in water using Swept-Frequency Acoustic Interferometry in H_2O along the fluid-vapor coexistence line*, in preparation.

B.T. Sturtevant, C. Pantea, D.N. Sinha, Accurate *sound speed determination of brine solutions*, in preparation.

B.T. Sturtevant, C. Pantea, D.N. Sinha, *A novel method for the determination of nonlinear parameter B/A in water*, in preparation.

B.T. Sturtevant, C. Pantea, D.N. Sinha, *Determination of nonlinear parameter B/A of fluids with high acoustical nonlinear parameter*, in preparation.



Multipurpose Acoustic Sensor for Downhole Fluid Monitoring

May 07, 2012

Cristian Pantea
Los Alamos National Laboratory

Track 1: High Temp Tools and Sensors, Drilling Systems, Zonal Isolation

Overview Slide

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- Timeline
  - Project start date: Oct 2009
  - Project end date: Sep 2012
  - Percent complete: 88 %

  * Received 71% of the original allocated funds. Re-casted delivered funds to cover a 3-year period.

- Budget

• Total project funding:	$ 1,138,450
• DOE share:	$ 1,138,450
• Awardee share:	$ 0
• Total spent:	88% ($ 998,615)

- Barriers
  - Site/Well Characterization Barrier D: Characterization – Subsurface environments in EGS regimes are inhospitable to existing downhole, *in-situ* characterization methods.
  - Demonstrate sensor capabilities that can be employed at a pressure of 22 MPa and operation temperatures of 374°C.

Project Management/Coordination

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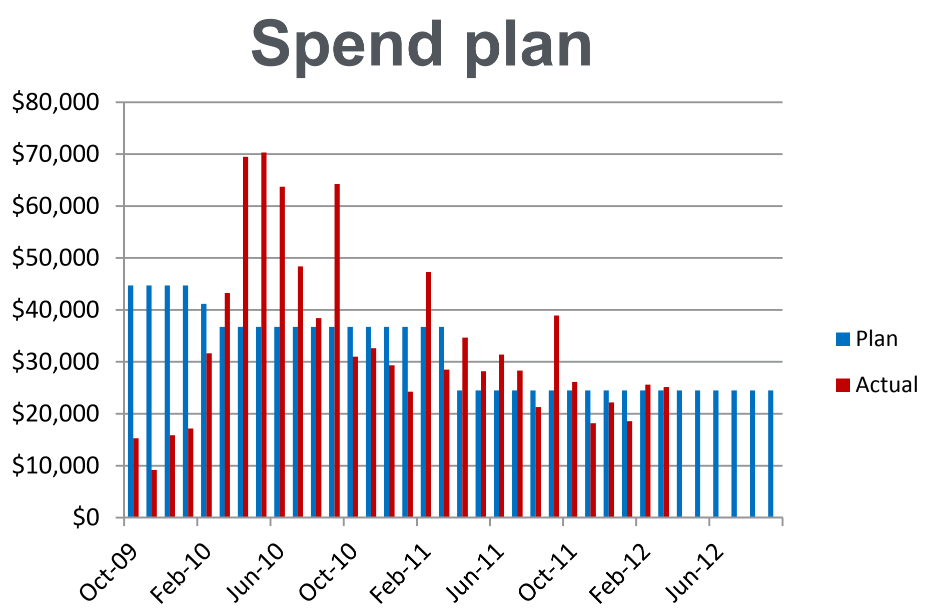
- Coordinating the work performed by the team.
- Coordinating and mentoring the Postdoctoral Research Associate hired to work on this project.
- Monthly checks on budget situation.
- Constant monitoring of work performed and future directions.
- Spending according to plan. Fluctuations are due to a slow start, and later on due to major equipment acquisition.



Collaborations

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- Project collaborators:
  - This project has no external collaborators

- Jobs created to date:
  - One job. We hired a Postdoctoral Research Associate that works full-time on this project. We intend to hire him in a full-time position, if new funding becomes available.

Relevance/Impact of Research

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- Novel sensor design ***based on acoustics***.
- Determine in **real-time** and in a **single sensor package** multiple parameters: temperature, pressure, fluid flow; and fluid properties, such as density, viscosity, fluid composition.
- Needed in nearly every phase of an EGS project, including Testing of Injection and Production Wells, Reservoir Validation, Inter-well Connectivity, Reservoir Scale Up and Reservoir Sustainability.
- Target pressure and temperature: 22 MPa and 374°C.
- Advantages:

  (1) low power consumption,

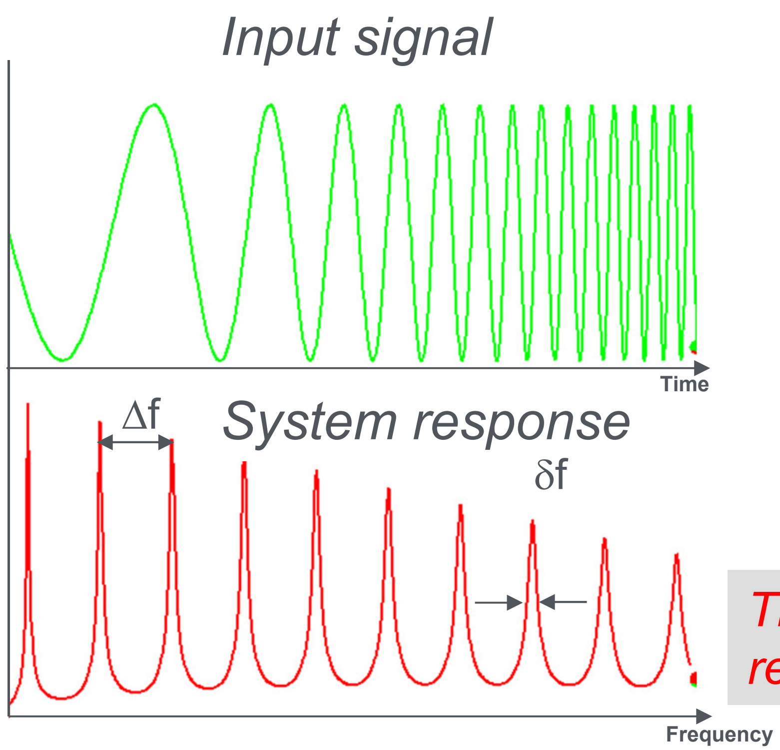
  (2) all solid-state and rugged,

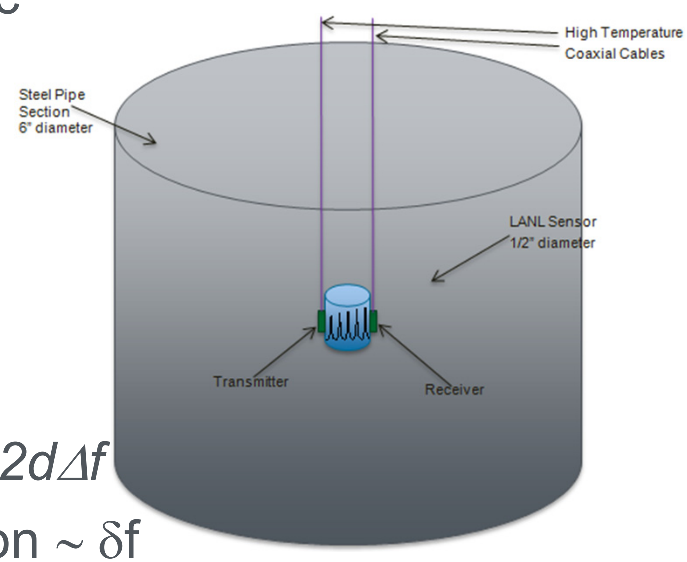
  (3) can withstand high temperature and pressure,

  (4) low cost, and

  (5) will replace 5-7 current instruments with a single one.

- The underlying physical basis of the sensing technique proposed here is the Swept Frequency Acoustic Interferometry (SFAI) technique and resonance tracking.





Sound speed = $2d\Delta f$

Sound absorption ~ δf

Δf =frequency spacing

δf =peak width

There can be hundreds of such resonance peaks in a typical spectrum

*Resonance-based methods are well-known for higher absolute accuracy and much smaller S/N ratio.

See, *e.g.* Migliori A, Sarrao J. Resonant ultrasound spectroscopy. New York: Wiley-Interscience; 1997.

Scientific/Technical Approach

Temperature

Temperature measurement independent of pressure, fluid composition or fluid flow

$LiNbO_3$ transducer advantages:

- very sensitive to temperature changes ~ 100 ppm/ºC
- very weak dependence on pressure changes ~ 100 ppb/psi

~ 250 ppm for 3500 psi (22 MPa)

* I. Nakagawa, J. Appl. Phys., vol. 44, No. 9, (1973) pp.3969

Pressure

Pressure measurement independent of fluid composition or fluid flow.
Has to be corrected for temperature.

Sound Speed
Sound Absorption
Fluid Composition

Data have to be corrected for temperature and pressure.

Fluid Flow

Fluid flow independent of temperature, pressure or fluid properties.

Key issues

- *Fluid composition* - provides geothermal reservoir properties.

- Borehole *temperature/pressure* - diagnostic measurements for geothermal reservoir characterization:

  - determines thermal/pressure gradient along the borehole

  - provides location of borehole fracture intersections

  - allows estimation of thermal drawdown and recovery rates of the circulating systems

  * The temperature provides diagnostic data during drilling, cementing, pressurization, and hydraulic-fracturing operations.

- *Fluid flow* determination provides fluid-flow patterns in a borehole. A typical borehole has fractures in several zones. The fluid flow can help characterize the man-made reservoir by:

  - determining the nature and location of the fractures,

  - determining the location and the amount of fluid that leaves and enters the borehole, and

  - determining the relative contribution of each fracture to the total reservoir.

Tasks, Schedule and Milestones

	Y1Q1	Y1Q2	Y1Q3	Y1Q4	Y2Q1	Y2Q2	Y2Q3	Y2Q4	Y3Q1	Y3Q2	Y3Q3	Y3Q4
Stage 1: Preliminary Investigation and Analysis												
Task 1: Materials identification.			M1									
				Gate 1								
Task 2: Theoretical modeling and algorithm development.											M2	
Stage 2: Concept Definition												
Task 3: Sensor geometry.							Gate 2			M3		
Stage 3: Concept Development												
Task 4: Flow measurement and fluid composition									M4			
											Gate 3	
Task 5: Temperature and pressure calibration.										M5		
Stage 4: Technology Development and Verification												
~~Task 6: Adapt design to existent hot rock project tool~~												
~~Task 7: Demonstration of proof of concept in laboratory~~												~~M6~~
	Oct-Dec 2009	Jan-Mar 2010	Apr-Jun 2010	Jul-Sep 2010	Oct-Dec 2010	Jan-Mar 2011	Apr-Jun 2011	Jul-Sep 2011	Oct-Dec 2011	Jan-Mar 2012	Apr-Jun 2012	Jul-Sep 2012

Due to change in funding (only 71% of initial funding was delivered), the scope of work had to be reduced. Also, the time period was extended to 3 years.

Accomplishments, Results and Progress

Task 1: Materials Identification → Identified materials and equipment needed for sensor development

(on schedule, started Oct 2009)

- Completed Jun 2010

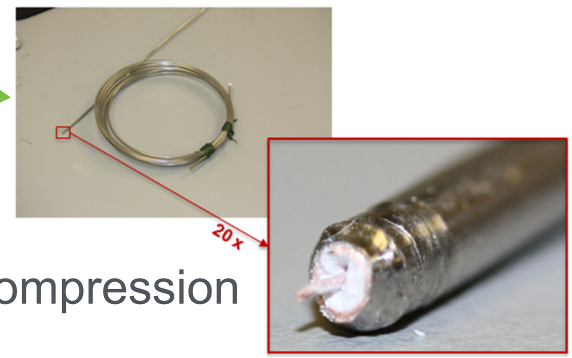
- **Piezoelectric transducers:**

  $LiNbO_3$: Curie temperature of 1150˚C; also investigated **$La_3Ga_{5.5}Ta_{0.5}O_{14}$**: > 1200°C.

- **High temperature coaxial cable:**

  Can be used at very high temperature: **600°C**

  and under **very aggressive media.**



- **Novel ruggedized sensor** constructed from Swagelok compression fittings and ConFlat flanges.

  Protects transducer crystal, thin-film electrodes and sensitive electrical connections from harsh temperatures and corrosive fluids.

- **High temperature bonding materials**

  Identified electrically insulating adhesive that withstands harsh test conditions.

  Have acquired several promising candidates for electrically conductive adhesives.

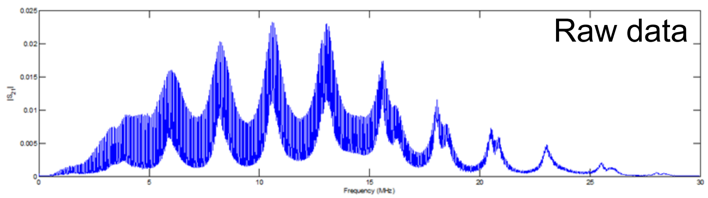
  Investigating direct metal-to-metal wirebonding for electrical connections.

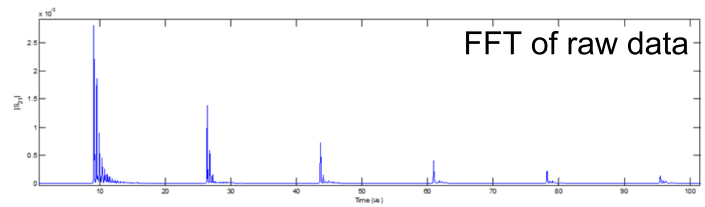
Task 2: Theoretical Modeling and Algorithm Development

(on schedule, started Jan 2010)

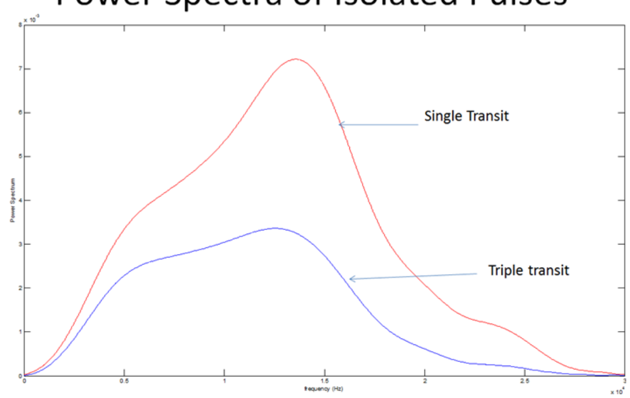
- Scheduled for completion: Sep 2012
- Developed Matlab code for sound absorption (α_L) determination

α_L ~ spectral ratio (B/A)



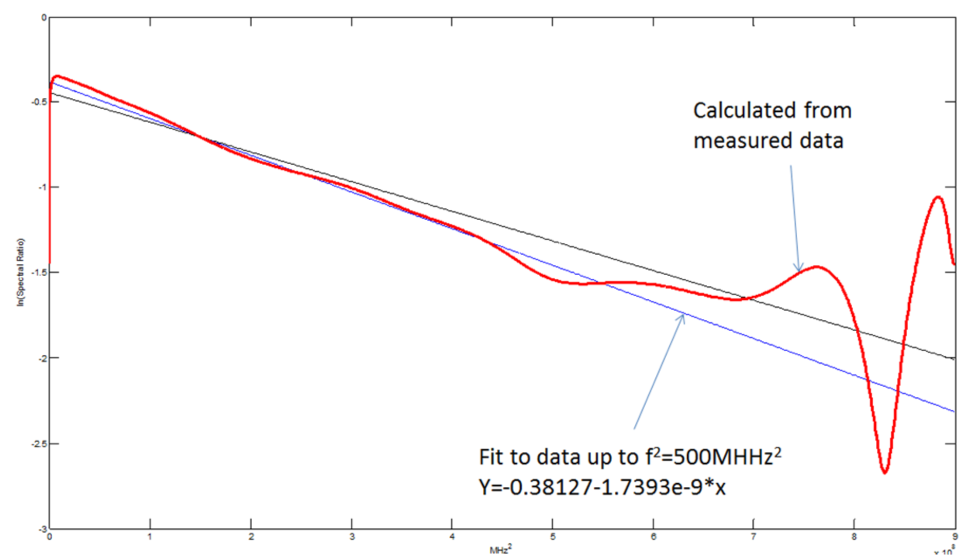


Power Spectra of Isolated Pulses



Theory: $$\ln\left(\frac{spectrumB}{spectrumA}\right) = -2\alpha L f^2 + \ln(R^2)$$

Lines fit to Spectral Ratio



*Good agreement with theory

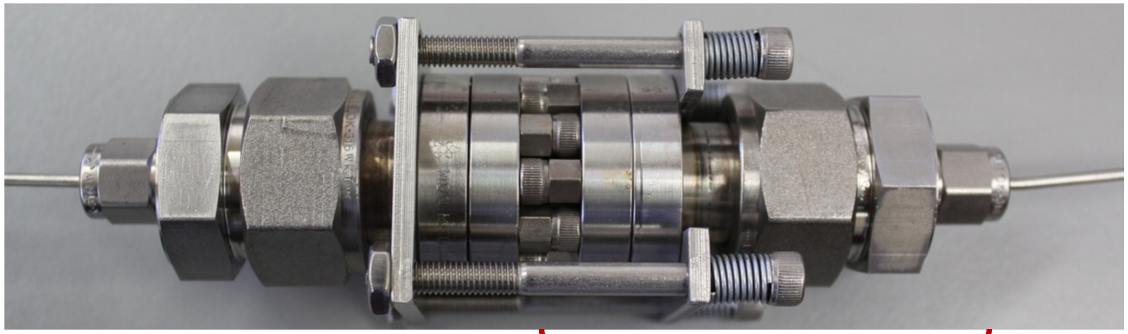
Task 3: Sensor Geometry

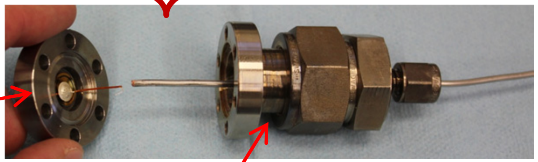
(on schedule, started Jul 2010)

- Scheduled for completion: Sep 2012
- Experimented with lithium niobate transducers mounted on different sensor geometries. Temperature/pressure range: 270ºC/22 MPa (as of Mar 2012).

→ Progressing according to schedule

Acoustic Interferometry cell





5 MHz $LiNbO_3$ transducer and 1-1/3" CF flange with d=1/2", h=1/8" well bored out. Transducer ground connected to flange.

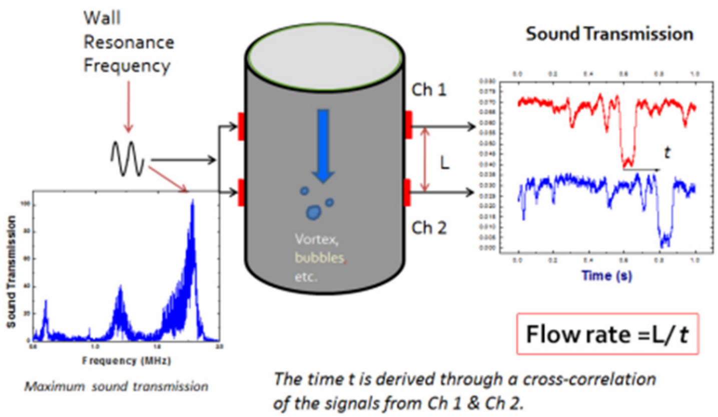
Standard 1-1/3" CF "half nipple" fitting with a 0.75" to 2 mm Swagelok reducing union to Accommodate 2mm stainless steel sheathed high temperature coax

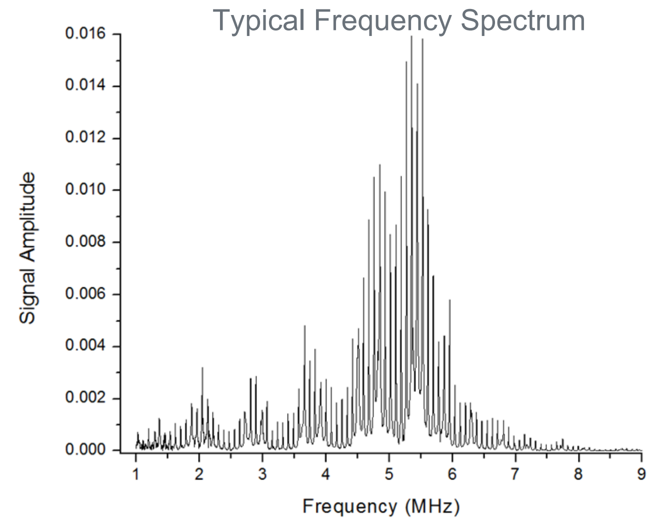
Task 4: Flow Measurement and Fluid Composition

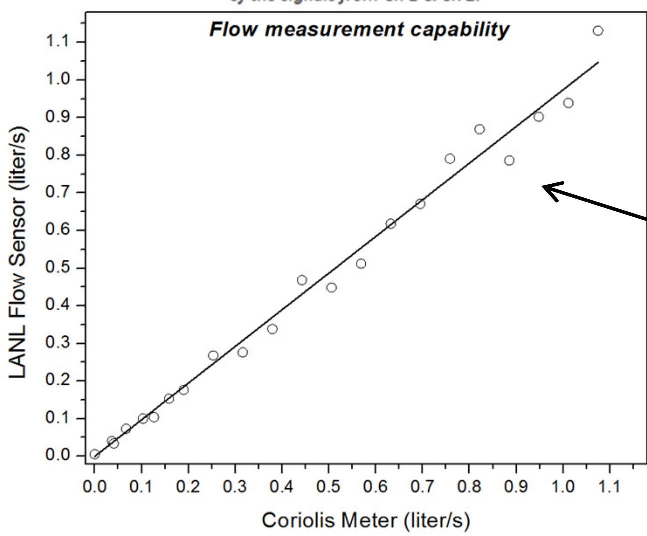
(on schedule, started 4/2011)

- Scheduled for completion: Sep 2012

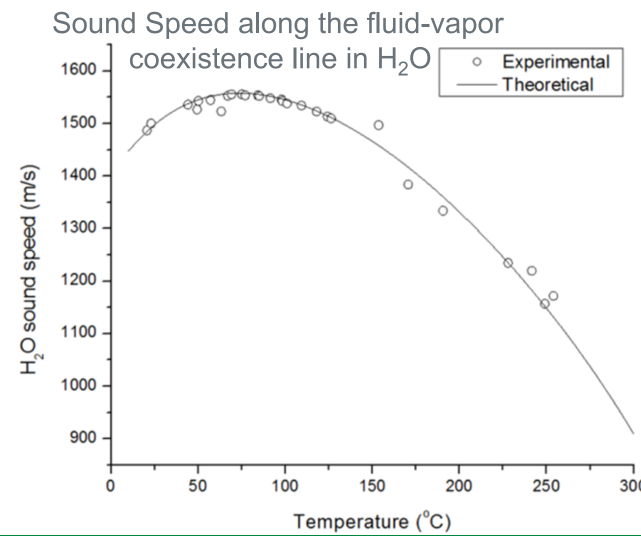
*** Current max temperature and pressure: 270ºC and 22 MPa (3500 psi)**







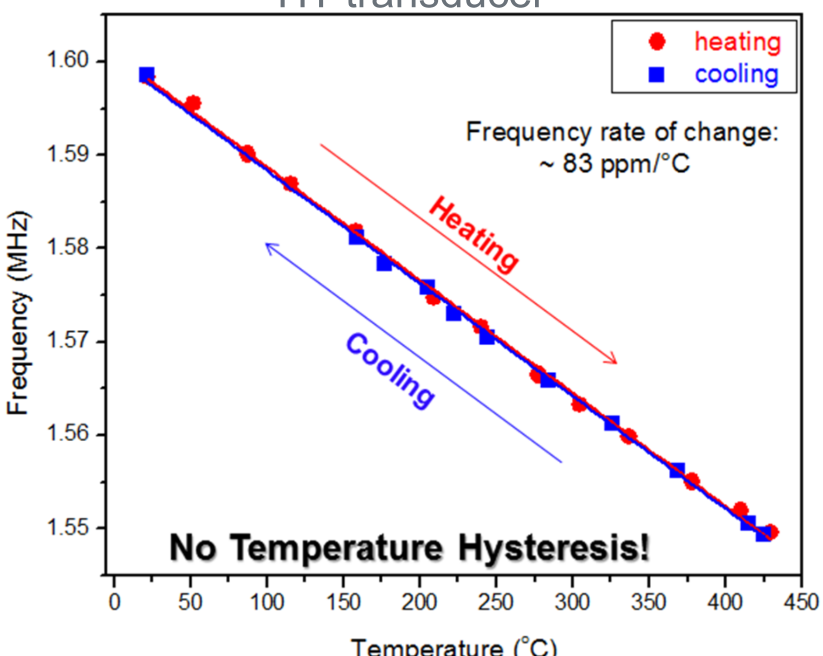
Measurements performed at room temperature



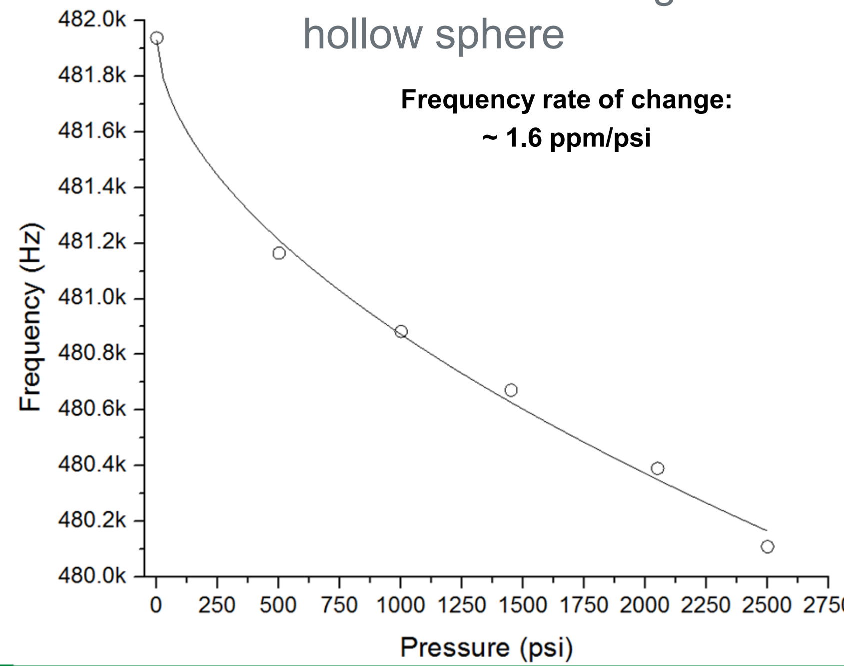
Task 5: Temperature and Pressure Calibration
(starts 7/2011)

- Scheduled for completion: Sep 2012
- Carried out temperature experiments with $LiNbO_3$ resonators in furnace and pressure experiments with hollow spheres in the pressure chamber. Demonstrated very good sensitivity to temperature and pressure change.

Acoustic resonance tracking of HT transducer



Acoustic resonance tracking of hollow sphere



Accomplishments, Results and Progress

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(1) High-priority technology needs into targeted technology focus areas. In the “Well Logging Tools” category, the target temperature for High Temperature Tools for year 2020, is 300ºC. Currently we are up to 270ºC, and we are confident we can improve on this by Sep 2012.

Well Logging Tools

Advance logging tool technology as applied to geothermal

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Higher temperature tools	Temperature (°C)	150-200°C	300°C	2020
Slimhole geothermal logging tools	Diameter (in)	150-200°C	≤3"	2016

(2) Technology needs specific to EGS reservoir characterization, creation, and sustainability/operation. In the “High Temperature Logging and Imaging Tools” category, the set target for 2018 is ±10% precision for pressure, temperature and flow. It is to be noted that our lab measurements have already reached the targets set for 2018.

High Temperature Logging & Imaging Tools

Real-time mass “fluxometer” and integrated pressure/flow/temperature tool

Technology Advancement	Technology Metrics			
	Metric Unit for Advancement	2011 Status	Target	When
Mass “fluxometer”	Mass flux accuracy (l/s)	NEW	+/- 0.2 l/s	2015
Integrated Pressure/Flow/Temp (PFT) Testing Tool	Precision (P, m/s, and T)	+/- 50%	+/- 10	2018

Data Sharing

- Type of data that is being generated from this project:

  - conceptual development of a high temperature acoustic-based sensor for temperature, pressure and fluid properties determination

  - generate numerical datasets related to brine physical properties at pressures and temperatures characteristic to EGSs

- As soon as new data are obtained, we will make them available to the "DOE Geothermal Data Repository" - currently under development by Boise State University. The DOE Geothermal Data Repository will be made public through the National Geothermal Data System, or retained in the DOE Geothermal Data Repository as business confidential, where applicable.

Future Directions

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The work on tasks 4 and 5 started, and the progress is according to the schedule

- ***Task 4: Flow measurement and fluid composition*** (Apr 2011 – Sep2012)
  – Milestone: Determine fluid composition and flow for fluids characteristic to EGS (M4).

- ***Task 5: Temperature and pressure calibration*** (Jul 2011 – Sep 2012)
  – Milestone: Determine the relationship between pressure, temperature and transducers resonances (M5)

Future Directions

- Future research and development:
  - Determine fluid properties for different brines specific to geothermal reservoirs.
  - Explore flow regimes comparable with flows found in geothermal reservoirs.
  - Determine the relationships between characteristic sensor resonances and pressure and temperature.

Summary Slide

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- Performed sound speed measurements up to 270ºC and tested components up to 374ºC.
- Performed pressure and temperature determination.
- Performed fluid flow measurements at room temperature in an in-house flow-loop.
- Modeling and analysis software development progressing according to schedule.

	FY2012	end of FY2012
Target/Milestone	Sensor geometry and materials that can withstand conditions specific to EGSs.	Fluid properties sensor tested to 374ºC and 22 MPa.
Results	Completed 3/2012	Tested to 270ºC and 22 MPa by 3/2012. Final testing scheduled for end of FY2012.